Cetacean Density Estimation from Novel Acoustic Datasets by Acoustic Propagation Modeling

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LONG-TERM GOALS

This project's long-term goal is the application and refinement of population density estimation methods based on detections of marine mammal vocalizations combined with propagation modeling. The density estimation method is applied to a novel acoustic data set, collected by a single hydrophone, to estimate the population density of false killer whales (*Pseudorca crassidens*) off of the Kona coast of the Island of Hawai'i.

OBJECTIVES

The objectives of this research are to apply existing methods for cetacean density estimation from passive acoustic recordings to novel data sets and cetacean species, as well as refine the existing techniques in order to develop a more generalized model that can be applied to many species in different environmental scenarios. The chosen study area is well suited to the development of techniques that incorporate accurate modeling of sound propagation due to the complexities of its environment. Moreover, the target species chosen for the proposed work, the false killer whale, suffers from interaction with the fisheries industry and its population has been reported to have declined in the past 20 years. Studies of abundance estimate of false killer whales in Hawai'i through mark recapture methods will provide comparable results to the ones obtained by this project. The ultimate goal is to contribute to the development of population density estimation methodologies that will be readily available to those involved in marine mammal research, monitoring, and mitigation.

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APPROACH

Approach to Estimating Population Density of False Killer Whales off Kona, Hawai'i

The methodology employed in this study to estimate the population density of false killer whales off Kona, Hawai'i, is based on the works of Zimmer *et al.* (2008), Marques *et al.* (2009), and Küsel *et al.* (2011). The density estimator formula given by Marques *et al.* (2009) is applied here for the case of one (k=1) sensor, yielding the following formulation:

$$\widehat{D} = \frac{n_c(1-\hat{c})}{\pi w^2 \widehat{P} T \hat{r}} \ . \tag{1}$$

In equation (1), n_c corresponds to the total number of auto-detected clicks in some time period *T*. The parameter $\hat{c}$ accounts for the false positive detections. The maximum distance, beyond which we don't expect to detect any calls, is given by *w*. The cue production rate (or click rate in this case) is dependent on available studies and information on animal acoustic behavior. Finally, the most important parameter in equation (1) for our methodology is the average probability of detection, $\widehat{P}$. This last parameter is obtained by running a Monte Carlo simulation in which the sonar equation is used to simulate the signal-to-noise ratio (SNR) of clicks from randomly distributed whales as would be received by the recording instrument. From literature information on the target species' diving behavior when emitting sounds, a 3D random distribution of simulated animals was created (Fig. 1) taking into account their orientations with respect to the hydrophone. The simulated animals are placed inside a circle in which the center is the hydrophone location and the radius corresponds to the maximum estimated detection distance for false killer whale clicks in the local environment, which, for simulation purposes, is taken to be 10 km. The sonar equation uses information on ambient noise levels, which were measured from the acoustic data set, transmission loss, which was calculated using an acoustic propagation model, and source levels and beam patterns of false killer whales, which were obtained from the literature. Simulated SNRs are then compared to those measured from the data set in the detector characterization curve, which gives a probability that the simulated SNR would be detected. The average probability of detection from all Monte Carlo realizations gives $\widehat{P}$ to be used in equation (1). Finally, by combining the total number of detected clicks, the number of false positive detections, the total time analyzed, the click production rate to the average probability of detection we will arrive at an estimate of the population density of false killer whales off the Kona coast for the time period analyzed.

WORK COMPLETED

The work completed in 2013 includes, 1) Devising a simple detector for false killer whale echolocation clicks, 2) The characterization of the detector, 3) Ambient noise measurements from the data set, and 4) Propagation model runs to simulate SNR of randomly distributed whales around the recording sensor location. Outstanding actions for this project include, 1) Estimation of false positive detections, 2) Running Monte Carlo simulations for the estimation of the average probability of detection ($\widehat{P}$ in Eq. (1)), and 3) Estimating density of false killer whales for the period of the data set being used.

1) Simple detector for false killer whale echolocation clicks

Automatic detections of false killer whale echolocation clicks had been provided to the project along with the raw dataset by Dr. Simone Baumann-Pickering (Scripps Institute of Oceanography). Their detection method was based on a two stage process as detailed in Roch *et al.* (2011) and Soldevilla *et al.* (2008), and provided us with the information that only a few days out of the 180 days the HARP

was deployed during 2010, actually had false killer whale detections. However, the task of characterizing their detector performance turned out to be a complex one. For density estimation problems, it is more important to characterize the detector as best as one can, than to have a detector with great performance (Küsel *et al.*, 2011). Therefore, a simple energy sum detector (Mellinger *et al.*, 2004) was devised in *Ishmael* (Mellinger, 2001) and ran through a period of the data set which had been identified by the previous two-stage detection to contain false killer whale activity. Two and a half hours of continuous data recorded on May 22nd, 2010, divided into 4 files of 37.5 minutes each, were chosen for the analysis.

### 2) Automatic Detector Characterization
In order to characterize the detector, a random 5-minute period of data (corresponding to approximately 3% of data) was picked and all false killer whale echolocation clicks were manually marked. Manual annotation of clicks was performed by visually and aurally inspecting 0.5-second spectrograms of data with the concurrent aid of softwares *Osprey* (Mellinger and Clark, 2006) and *Triton* (Wiggins, 2003). *Osprey* was then used to measure the power of each annotated click in the same frequency band used in the auto detector, 20-60 kHz. Click power measurements (in dB) were subtracted from the mean ambient noise value (in dB) in the same frequency band to obtain the signal-to-noise ratio (SNR) of the clicks. Manually detected clicks, which are considered as ground truth, were compared to auto detected ones in the same time period, and the binomial probability was calculated for 20 SNR bins between the minimum and maximum values observed in the 5-minute data set. Finally, the software *R* (R Foundation for Statistical Computing) was used to fit a generalized additive model (GAM) to the probability data, and 10.000 realizations of the mean probability curve, to be used in the Monte Carlo simulation, were also computed.

3) Ambient Noise Measurements
Ambient noise data is used in the calculation of signal-to-noise ratio of manually annotated clicks (data component) and also in the sonar equation for the simulation of click SNR (simulation component). Usually, when calculating call SNR from the data, a "noise" window prior to the call is used. However, picking a time window prior to each call can introduce errors in the analysis. In the specific case of our data set, "noise" windows prior to clicks most often contained whistles, reverberation from previous clicks, or were non-existent, that is, clicks were too close to each other, making it impossible to assign a specific time window from which to measure ambient noise. It is also noted that a time window for noise measurement, in the frequency domain, should be long enough so that enough samples are present for the averaging of bins in a specific frequency band of interest. Finally, since these noise values are also used in the sonar equation for simulation of click-SNR, time samples without boat, reverberation, or any other noise sources are required. Therefore, it was decided to visually inspect the four data files from May 22nd, 2010, which contained false killer whale clicking activity and manually label time periods without man-made (boat noise) nor biological noise (clicks and whistles) activity.

4) Acoustic propagation model runs
The propagation model Bellhop (Porter and Bucker, 1987) is used here to calculate transmission loss (TL) from each of the 10,000 randomly distributed "animals" to the HARP location (Fig. 1). A mean sound speed profile calculated from data collected in 24 oceanographic stations in the area of the HARP deployment, in July of 2011, was used as input for Bellhop. Bottom properties were chosen to reflect the volcanic nature of the area's ocean bottom with little sediment cover.
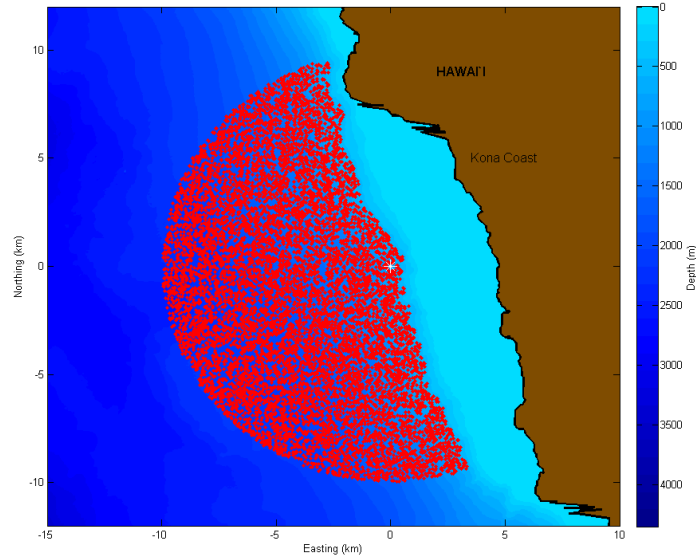
Figure 1. Kona Coast of Hawai'i showing location of HARP deployment (white dot in the center of semi-circle) and random distribution of 10,000 simulated whale locations (red dots) around the hydrophone where bathymetry is deep enough for them for perform foraging dives and hence produce echolocation clicks.

Initially, a false killer whale peak frequency of 40 kHz (Madsen *et al.*, 2004) was used in the TL calculation. However, the highly broadband nature of false killer whale foraging clicks, especially as observed in the data set, required re-evaluating the methodology. Transmission loss values are calculated to be used in the sonar equation to estimate the SNR of clicks produced in different locations around the recording instrument by also taking into consideration the animal's beam pattern and orientation with respect to the sensor. That being said, it is noted that the sonar equation was developed for CW tones. The question then becomes, what is the best, or correct, way to simulate broadband signals using the sonar equation, and hence correctly estimate the average probability of detection $\hat{P}$ to be used in equation (1)?

RESULTS

### 1) Results on the auto-detection of false killer whale echolocation clicks
Click detection was performed in the frequency domain by choosing the same spectrogram parameters as those used to manually annotate clicks for the detector characterization step, i.e. using a 512-point FFT, with 50% overlap and Hann window. Energy was summed in the frequency band from 20 to 60 kHz, which not only corresponded to data found in the literature (Madsen *et al.*, 2004) but was also observed in the current data set (Fig. 2). A detection threshold of 0.7 was chosen in the energy sum method yielding a total of 260,973 clicks detected in 2.5-hour period of continuous data.
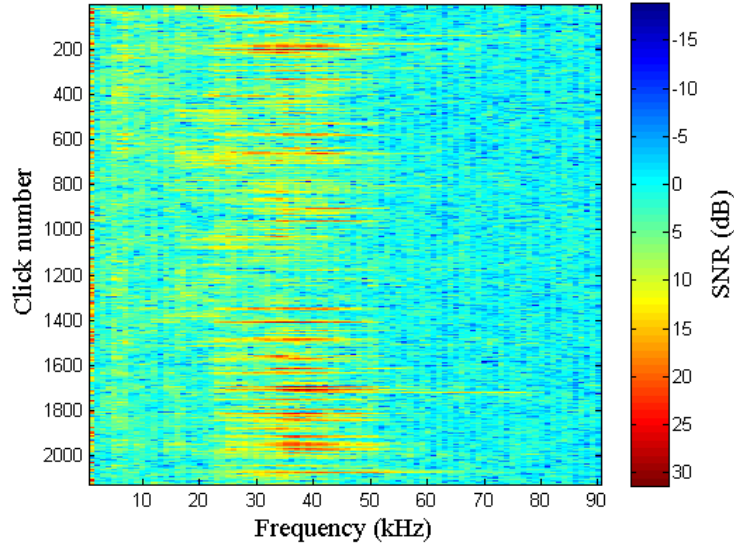
Figure 2. Signal-to-noise ratio of 2124 manually labeled false killer whale clicks, calculated in 1 kHz band intervals from 0 to 90 kHz. From the above image it can be observed the majority of the clicks energy is concentrated in the 20 to 60 kHz band.

2) Results on the characterization of the detector

Start and end times of clicks in a random 5-minute period of data recorded May 22nd, 2010, were carefully marked and logged using a 512-point FFT, with 50% overlap and Hann window. It should be noted here that only those clicks that showed up in the spectrogram as perfect coherent lines were annotated, that is, clicks that showed up with signs of reverberation were not considered. The main reason for this distinction is that the effect of reverberation cannot be incorporated in the modeling component when simulating click SNR. This manual analysis yielded a total of 6512 clicks. Comparison of manual and auto detected clicks yielded 4667 clicks that were detected by both methods. By applying a binary scheme to the 6512 manual detections, that is, assigning a value of 0 if it was not detected by the auto detector, and 1 if it was detected by the auto detector, and by dividing the measured SNRs into 20 bins between the minimum and maximum measured values, a probability of detection plot as a function of SNR was obtained (Fig. 3). Ten thousand realizations of the GAM fit to the probability of detection data were also obtained (Fig. 4) for later use in the Monte Carlo run to simulate click SNR from 10,000 random distributed false killer whales around the recording sensor location.
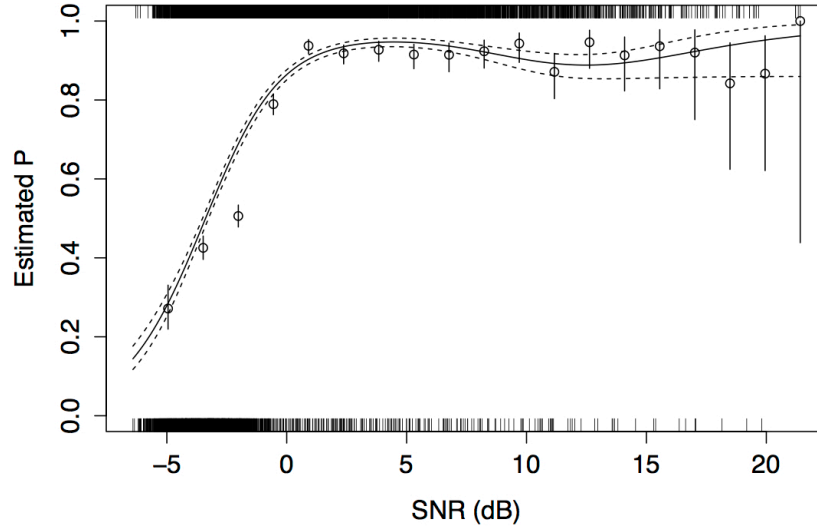
Figure 3.The characterization of the auto detector is done by estimating the probability of detection based on click SNR, yielding the above plot. Circles represent the data points for each SNR bin with 95% binomial confidence intervals (vertical lines). Black curve is the GAM fit to the data and dashed lines are the 95% point-wise confidence intervals. Vertical lines on top of the plot correspond to the 4667 clicks detected by both manual and auto detectors. Vertical lines on the bottom of the plot correspond to the 6512-4667 clicks that were not detected by the auto detector.
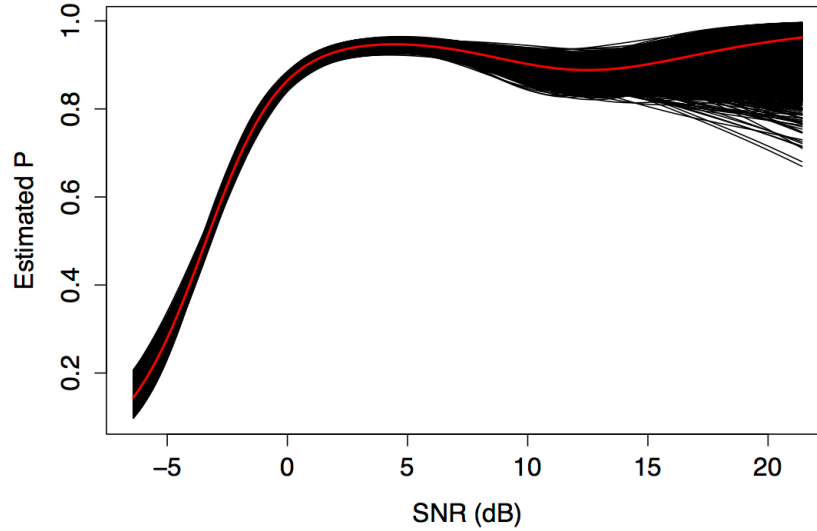

Figure 4. 10,000 realizations of the GAM fit to the probability of detection as a function of SNR curve shown in Fig. 1. Red curve corresponds to the original fit to the data.

3) Results on measuring ambient noise

Each 37.5-minute file was visually inspected every 5 seconds for quiet time periods, without signs of significant noise sources such as shipping noise, and biological sounds. By using hand-picked time windows in the same data set one is looking for calls, it is guaranteed that true ambient noise is being measured. Such analysis yielded 237 quiet time windows. The power of each quiet time period was measured in the same manner as was done for manually labeled clicks. Measurements were performed in 1 kHz band intervals from 0 to 90 kHz, to observe the general behavior of ambient noise, and also in the 20 to 60 kHz band, in order to calculate click SNR. Noise spectrum levels in dB re $1\mu Pa^2$/Hz were obtained by applying the following formula (Au, 1993):

$$NL = 20\log_{10}(N) - 10\log_{10}(\Delta f), \qquad (2)$$

where N is noise pressure level, and Δf is the bandwidth in Hz in which the measurements were taken. Results of noise spectra relative to the level at 10 kHz are shown in Fig. 5.
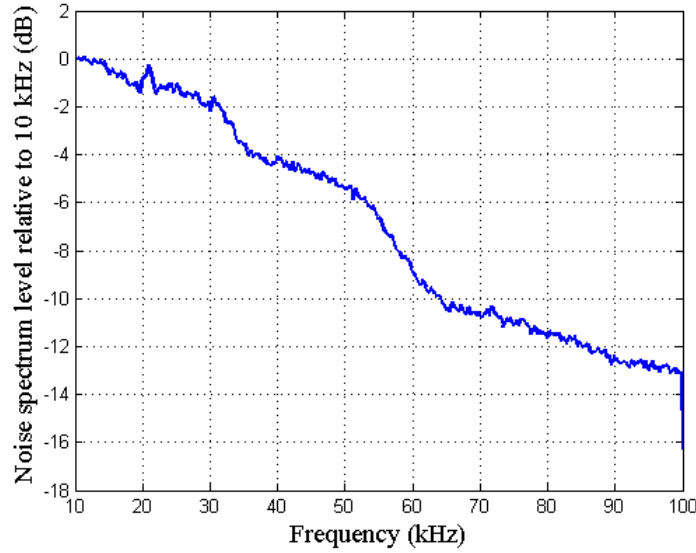
Figure 5. Noise spectrum levels relative to 10 kHz as measured from the data set, showing the variation in noise levels in the frequency band of false killer whale echolocation clicks. Note that between 20 and 60 kHz, which is the frequency band used in the auto-detector, noise varies by at most 10 dB.
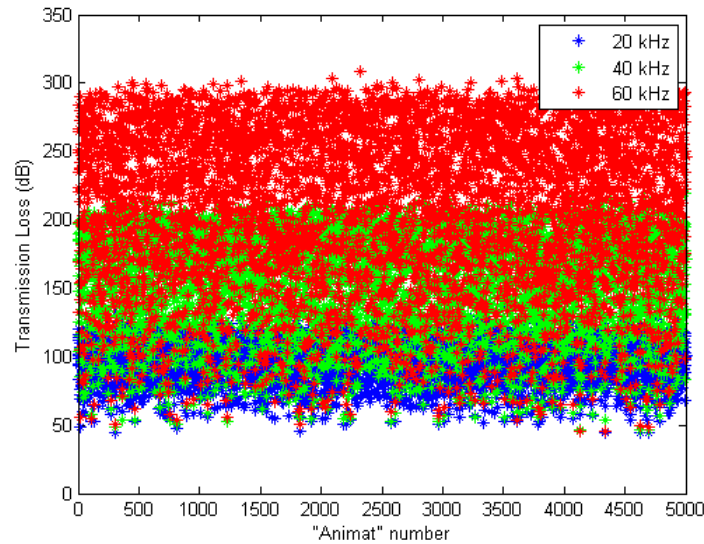
4) Results on transmission loss calculations

Results of transmission loss calculations are currently being investigated to determine if using the peak or center frequency of the highly broadband clicks of false killer whale is enough to obtain reasonable estimations of detection probability. Considering the sonar equation,

$$SNR = SL - DL - TL - NL, \qquad (3)$$

where SL comes from a distribution of on-axis source levels, and DL is directionality loss, which depends on the off-axis angle between whale and hydrophone, it is expected that TL will have the most variation, and hence a bigger contribution in the calculation of SNR and estimation of probability of detection. Figure 6 shows TL values in dB calculated for each animal location (Fig. 1) for 20 (lower

detector frequency), 40 (peak frequency), and 60 (upper detector frequency) kHz. As frequency increases, so does transmission losses, which is associated with higher absorption losses. For simulated animals that are farther away from the recording sensor, it is expected (based on Fig. 6) that differences in *TL* from 40 to 60 kHz can be on the order of 100 dB. On the other hand, looking at the relative noise levels in Fig. 5, the difference in ambient noise for the same frequencies is only 4 to 5 dB.

Figure 6. Transmission loss results for 5,000 simulated whales (Fig. 1) and for three different frequencies: 20, 40 and 60 kHz.

IMPACT/APPLICATIONS

The application of recently developed density estimation methods to different data sets and marine mammal species provides opportunities to test the methodology and make it more general. It was noted however that such methodology is not a "one size fits all," since, as observed in the present study, the frequency band of calls will influence, for example, how to appropriately simulate them. When studying species that are considered threatened or endangered in any way, as is the case with false killer whales in Hawai'i, it is hoped that density estimation methods from passive acoustics can become a tool to help monitor, study and protect those populations. Development of more efficient and accurate propagation modeling practices, by performing convergence tests and propagating the field straight to each simulated animal instead of performing interpolation, to be used in estimating the probability of detection of marine mammal calls is also an interesting component of this project. The ultimate goal is to develop easy-to-use software to make density estimation readily available to the Navy and to those involved in marine mammal research, monitoring, and mitigation. By improving our capabilities for monitoring marine mammals we hope to contribute to minimizing and mitigating the impacts of man-made activities on these marine organisms.

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